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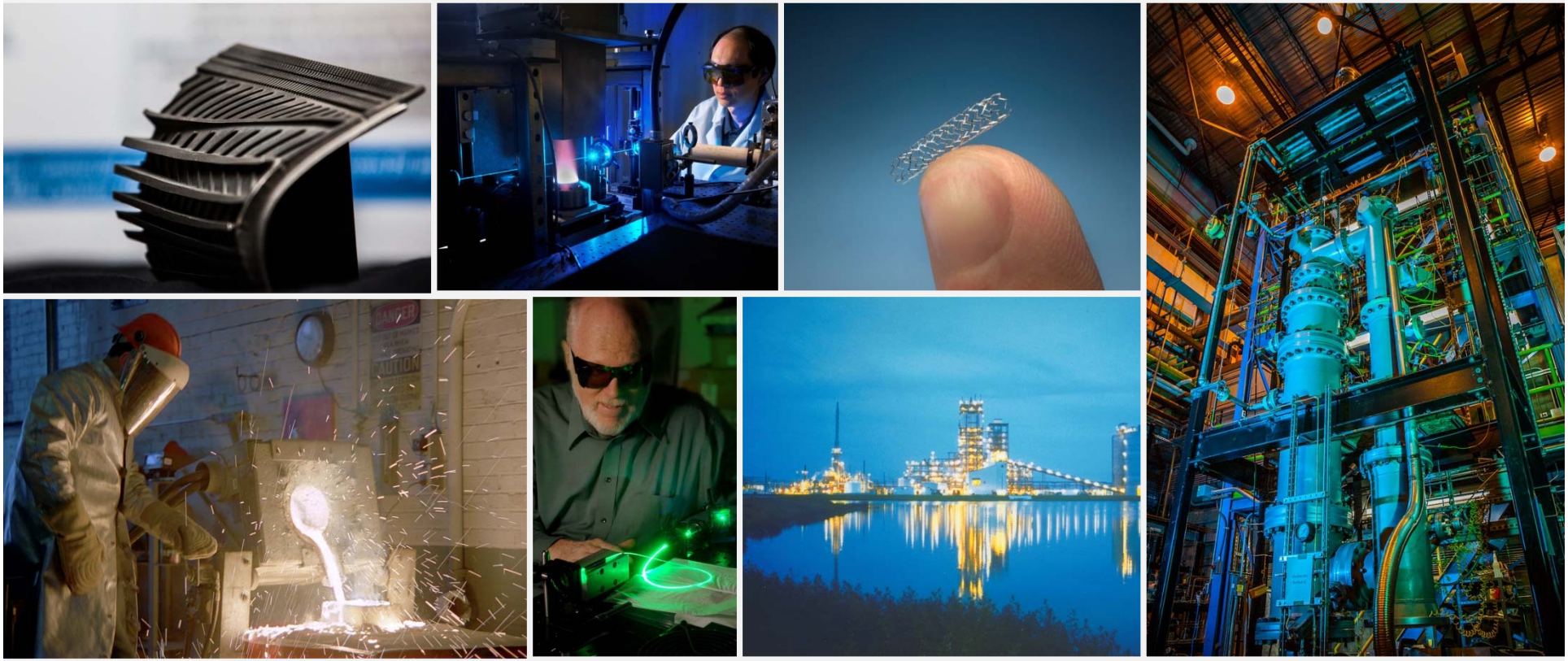

Coal-Hybrid Power Systems for the Future

DOE/NETL-2016/1804

US DOE NETL – Research & Innovation Center

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U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

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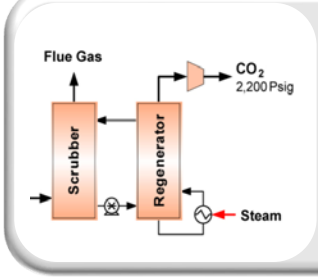
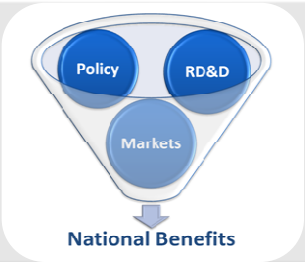
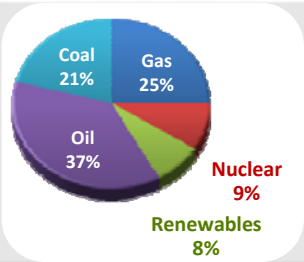
Analyses



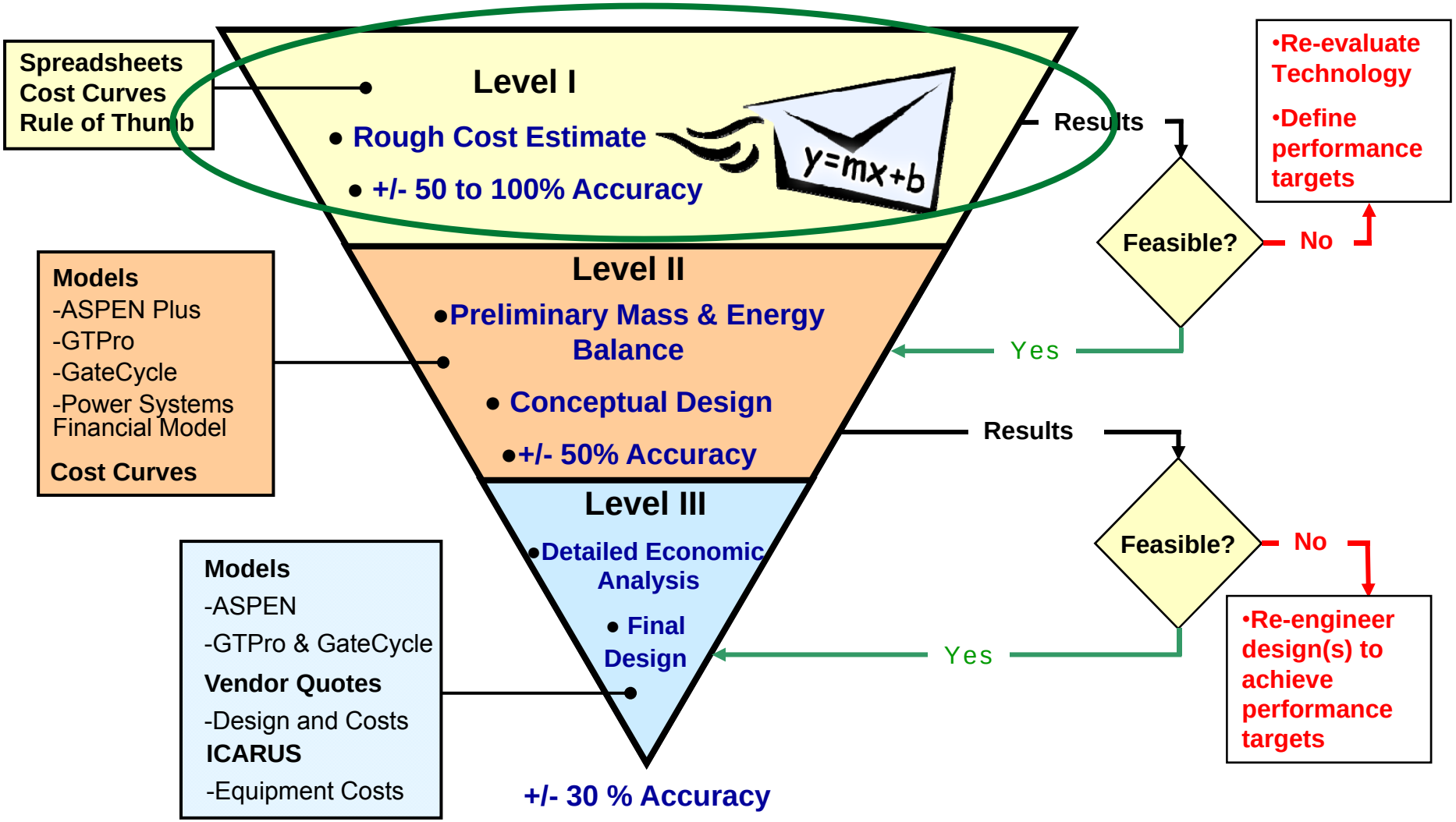




Technologies	Benefits	Situations & Trends	Integrated Electric Power Systems
Drivers			
• *Technology evaluation* • *Process & cost engineering* • *R&D targets*	• *Policy scenarios* • *Market deployments* • *National benefits of R&D*	• *Current conditions* • *Future scenarios*	• *Cost of electricity* • *System design & integration*

Analysis Categories

Choosing the Right Tool for the Right Job



Importance of Coal

Value of Developing Coal Energy Technologies

- Cheap & Abundant: Coal prices historically low and stable over time
- Ease of Transport & Storage:
  - Spills and explosions a non-issue, multi-modal transport infrastructure in place
  - Multi-month stockpiles are the norm (not the case for natural gas and biomass storage)
- Good Backstop Fuel: Easily used in other solid fuel energy systems
- Burgeoning Use in Developing Nations:
  - Developing nations are expanding coal use as they industrialize
  - High efficiency technologies can dramatically reduce long-term emissions growth

What is the Path Forward?

- Identify pathways for coal to compete on both a cost and emissions basis
- Pathways must enable expanded use of renewable energy
  - Support and even leverage intermittent nature of certain renewable technologies
  - Bring down the cost of large scale integration

Pathways to Future Coal Usage

- **New Coal Power Technologies**
  - High efficiency, next-generation conversion pathways
  - Carbon, Capture, and Utilization/Storage pathways
- **Hybrid: Novel Energy Systems**
  - Integration of renewables: thermal or electrical integration
  - Integrated energy storage: reduces emissions, leverages intermittents
- **Hybrid: Multi-Fuel Operation**
  - Enable feedstocks which are otherwise constrained due to cost, availability, or price volatility
  - Coal acts as the "flywheel", or enables economies of scale while lower-carbon fuel provides emissions benefits
- **Hybrid: Diverse Product Slate**
  - Combined Heat and Power (CHP)
  - Poly-generation of electricity and higher value products (chemicals, fuels)

New Source Performance Standard (NSPS) is 1,400 lb CO_2/MWh_{gross} for coal.

Coal Hybrids: Selected Pathways
Analysis Scope

This Level 1 screening analysis evaluates how advances in cycle and process efficiency can be combined with other technologies in order to build a coal-fired power plant that meets the NSPS of 1,400 lb CO_2/MWh_{gross}

<u>What is evaluated:</u>

- **Advances in Process and Cycle Efficiency**
  - Three Levels of Coal-fired Power Plant Efficiency
  - Current state-of-the-art (SOA) through reported next-generation Advanced Ultra-supercritical (AUSC)
- **Alternative Technology Pathways**
  - Direct Integration of Renewables with Conventional Power Plants
    - Solar-Assisted Feedwater Heating (SAFWH)
    - Direct Renewable Integration of Wind and Solar PV
  - Heat Integration with Other Generation Types (e.g. Fuel Cell)
- **Performance of each technology pathways is evaluated at all three Coal-fired Power Plant cycle efficiencies**

Coal Hybrids: Selected Pathways

Scope: What was Omitted?

Several Technology Pathways were Omitted from this Analysis…

- Integrated Gasification Combined Cycle (IGCC) plants
- Oxy-Combustion
- Carbon Capture and Storage (CCS)
- Biomass Co-firing
  - 5 to 10% (by weight) biomass can be co-fired without boiler modifications in normal pulverized coal systems
  - 30% or more biomass can be co-fired in Circulating Fluidized Bed (CFB) systems
  - EPA hasn't qualified biomass as emissions reduction pathway for NSPS
- Combined Heat and Power (CHP) Offtake
- Retrofits to existing power plants

Direct Renewable Integration

Integrate renewable resources directly at power plants to reduce emissions.

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Direct Renewable Integration

Pathway Overview:

Directly integrate intermittent generation from solar PV or wind to run auxiliary equipment (balance of plant electric loads) and boost output.

Status: *Demonstration Scale*

- **Certain commercial plants have limited capacity of renewable energy co-located at the power plant**
- **Commercial-scale plant is under construction in South Korea which will integrate modest amounts of renewable energy (hydropower & solar PV)**

Potential Impact: *Increased Efficiency or Peak Output*

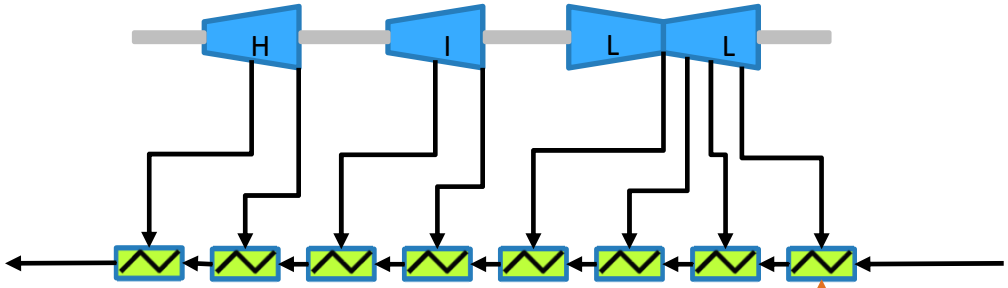
- **Multiple configurations possible:**
  - Run aux equipment when available
  - Integrate electrical storage for further reductions
- **Reduced emissions or boosted output when renewables are available**

Concern: *May not be applicable to NSPS*

- **Unclear if this reduces emissions on "net" or "gross" basis**

Solar-Assisted Feedwater Heater

Coal Plant Steam Turbine Feedwater System



Various Applicable Solar Technologies

- Low (300°F) or high (700°F) temperature
- Full or partial feedwater heating

Feedwater Heating

- Reduces/removes steam bleeds
- Increases power output
- Lowers emissions

Solar-Assisted Feedwater Heater

Pathway Overview:

Integrates concentrated solar thermal energy to heat up feedwater sent to the boiler in a thermal power plant.

Status: *Demonstration Scale*

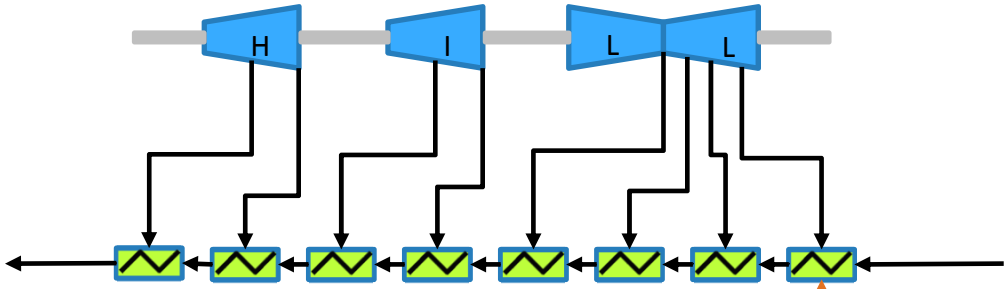
- **One domestic demonstration occurred in Colorado starting in 2010**
  - Project Cost: $4.5 million (2010$)
  - Designed to add 1 MWe of output to a 49 MW_e plant
  - Project designed to run for 1 year
  - Ceased operation in 2012 after the planned demonstration
- **NGCC Commercial Offering exists: Installed Capacity is unknown**

Potential Impact: *Increased Efficiency or Peak Output*

- **Can improve the power plant efficiency by 1.5% to 7% (on a relative basis) for low temperature systems**
- **Substantial efficiency improvements possible if high pressure feedwater heater (HPFWH) is replaced (16% to 28% on a relative basis)**
- **System could also be configured to boost peak power generation during summer peak loads**

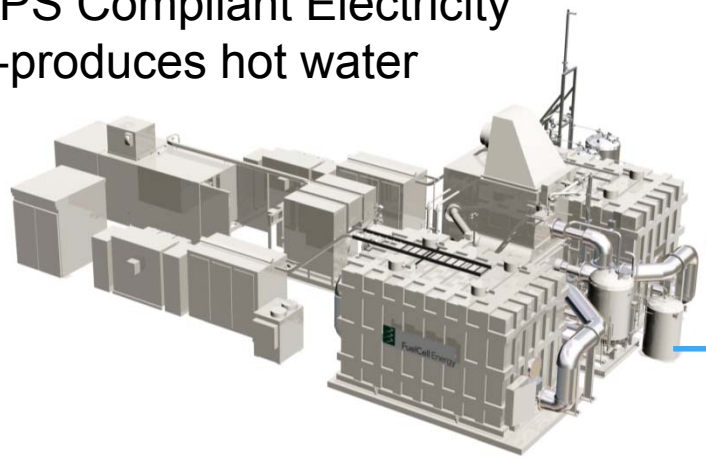
Direct Integration of Other Generation

Coal Plant Steam Turbine Feedwater System



Farm of NG-fired Fuel Cells

- NSPS Compliant Electricity
- Co-produces hot water



Feedwater Heating

- Reduces/removes steam bleeds
- Increases power output
- Lowers emissions

Electricity Sold into Grid

Direct Integration of Other Generation

Pathway Overview:

Co-locates a commercial fuel-cell generator and integrates waste heat to heat up feedwater sent to the boiler in a coal thermal power plant.

Status: *Demonstration Scale*

- **Similar to SAFWH demonstration**
- **Utilizes a commercially available natural-gas fuel cell for high availability**

Potential Impact: *Increased Efficiency and Fuel Diversity*

- **Fuel cell provides efficient, NSPS-compliant generation (980 lb CO_2/MWh)**
- **Coal thermal plant efficiency can be increased significantly:**
  - Can improve the power plant efficiency by 1.5% to 7% (on a relative basis) for low temperature systems which replace the low pressure feedwater heater (LPFWH)
  - Substantial efficiency improvements possible if HPFWH is replaced (16% to 28% on a relative basis)
- **System could also be configured to boost peak power generation**

Coal Hybrids: Methodology

Advances in Cycle Efficiency

"…analysis evaluates how advances in cycle and process efficiency can be combined with other technologies in order to meet new NSPS criteria…" (slide 8)

Three Levels of Coal-fired Power Plant Efficiency Evaluated:

- **State of the Art (SOA)**
  - Supercritical PC (NETL Baseline case B12a)[1]
  - 40.7% efficiency (HHV)
- **High-Efficiency Ultra-Supercritical (USC)**
  - Trianel Kohlekraftwerk Lünen is one of the world's most efficient coal power plants[2]
    - » 45.95% efficiency (LHV) (or ~44% (HHV)), fired on bituminous coal
    - » Fast Ramping to balance intermittent wind and solar
    - » Began electricity sales in North Rhine-Westphalia, Germany in December 2013
  - Represents the Current "Bleeding Edge" of efficient coal generation
- **"Next Generation" Advanced USC (AUSC) Technology**
  - EPRI reports "Next Generation" AUSC is at Technology Readiness Level 5 (TRL 5)[3]
  - ~45% efficiency (HHV) at 760°C[4]
- **Each plant is designed for a net output of 550 MWe**

[1] *Cost and Performance Baseline for Fossil Energy Plants Vol 1a, Bituminous Coal (PC)… Revision 3*. NETL, July 6, 2015, DOE/NETL-2015/1723.
[2] *Setting the Benchmark: The World's Most Efficient Coal-Fired Power Plants*. Cornerstone Magazine, March 16, 2015.
[3] *Can Future Coal Power Plants Meet CO2 Emission Standards Without Carbon Capture & Storage?* EPRI, October 2015.

Coal Hybrids: Methodology

Renewable & Other Technology Integration

- **Direct Integration of Wind and Solar PV: Technology Parameters**
  - Current (EIA) and "next generation" capacity factors (CF) from NREL
  - Current SOA costs
  - Wind only case, Solar only case, and Mix (60% solar, 40% wind)
- **Energy Storage**
  - Lead Acid and Lithium Ion Battery Storage for "Direct Integration" Cases
    - » Cycle data not accounted for in screening study
    - » Macro-level examination of storage requirement based on annual CF
  - Thermal Energy Storage evaluated for Boiler FW Heating
- **Boiler Feedwater Heating**
  - Determine efficiency improvements required to meet targets
  - Screen high-pressure FW heating (HPFWH) cases
  - Evaluate cost & area required for two different geographic locations
- **Fuel Cell Direct Integration**
  - Commercially available Fuel Cell, 2.8 MW_e + Heat Integration

Coal Hybrids: Methodology

Meeting the Targets

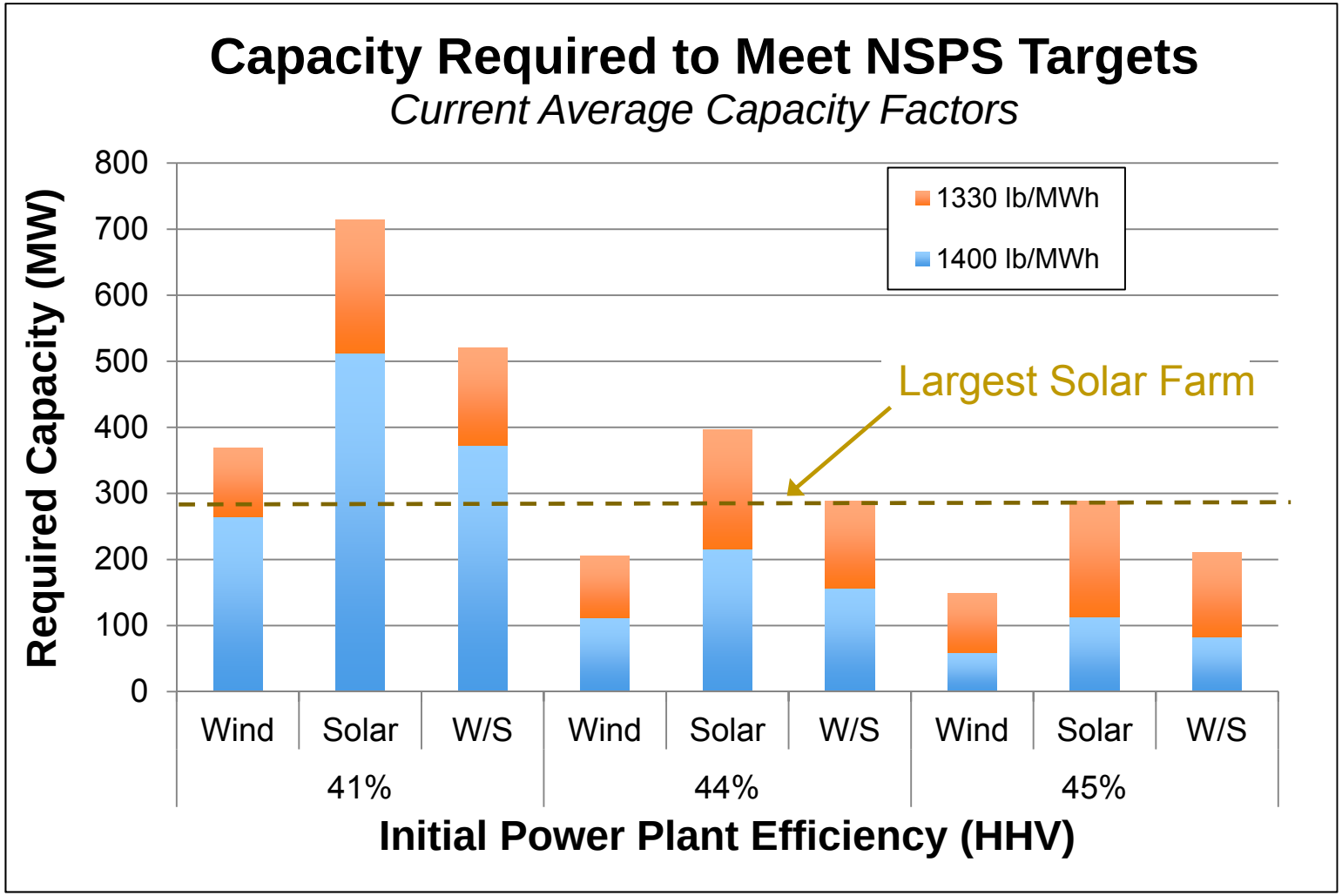
"…analysis evaluates how advances in cycle and process efficiency can be combined with other technologies in order to meet new NSPS criteria…" (slide 8)

What is the appropriate emissions target for NSPS compliance?

- **Target set by the EPA and listed in the Federal Register:**
  - 1,400 lb CO_2/MWh-gross (annual basis)
- **Evaluate an additional, more stringent target as a sensitivity case**
  - 1,330 lb CO_2/MWh-gross (annual basis) as additional target
    - » 5% below the 1,400 limit
  - Accounts for operational and other perturbations that could reduce efficiency and increase emissions:
    - » During startup and shutdown, the plant will have higher emissions than during steady state operation
    - » Fast ramping or load-following (flexible operation) can negatively impact efficiency, and therefore emissions
    - » Other perturbations could occur, including fuel quality issues

Direct Integration Results

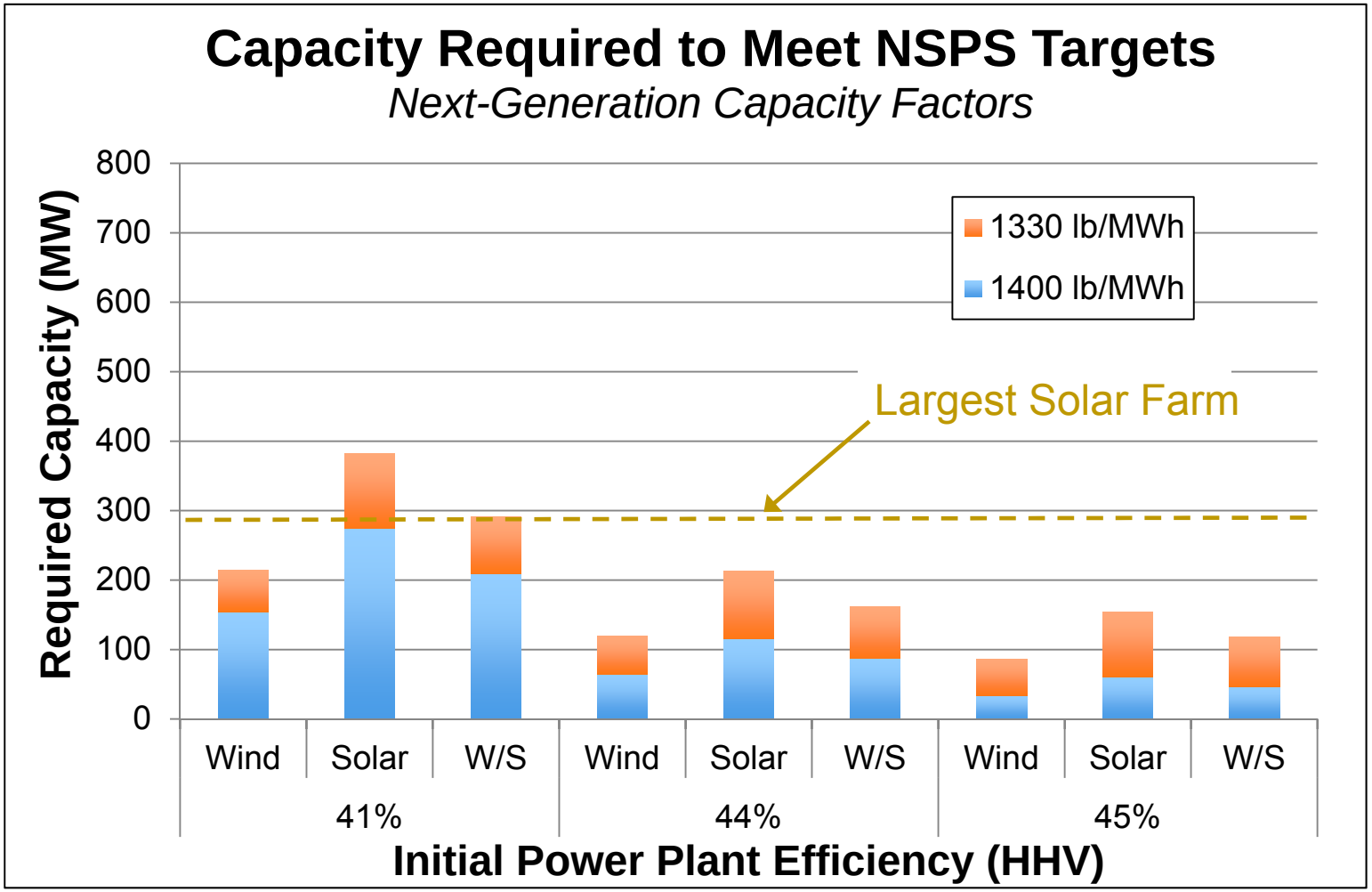
Wind & Solar PV Capacity Requirements



EIA Annual Capacity Factors, Top of Range: http://www.eia.gov/electricity/annual/html/epa_02_02.html

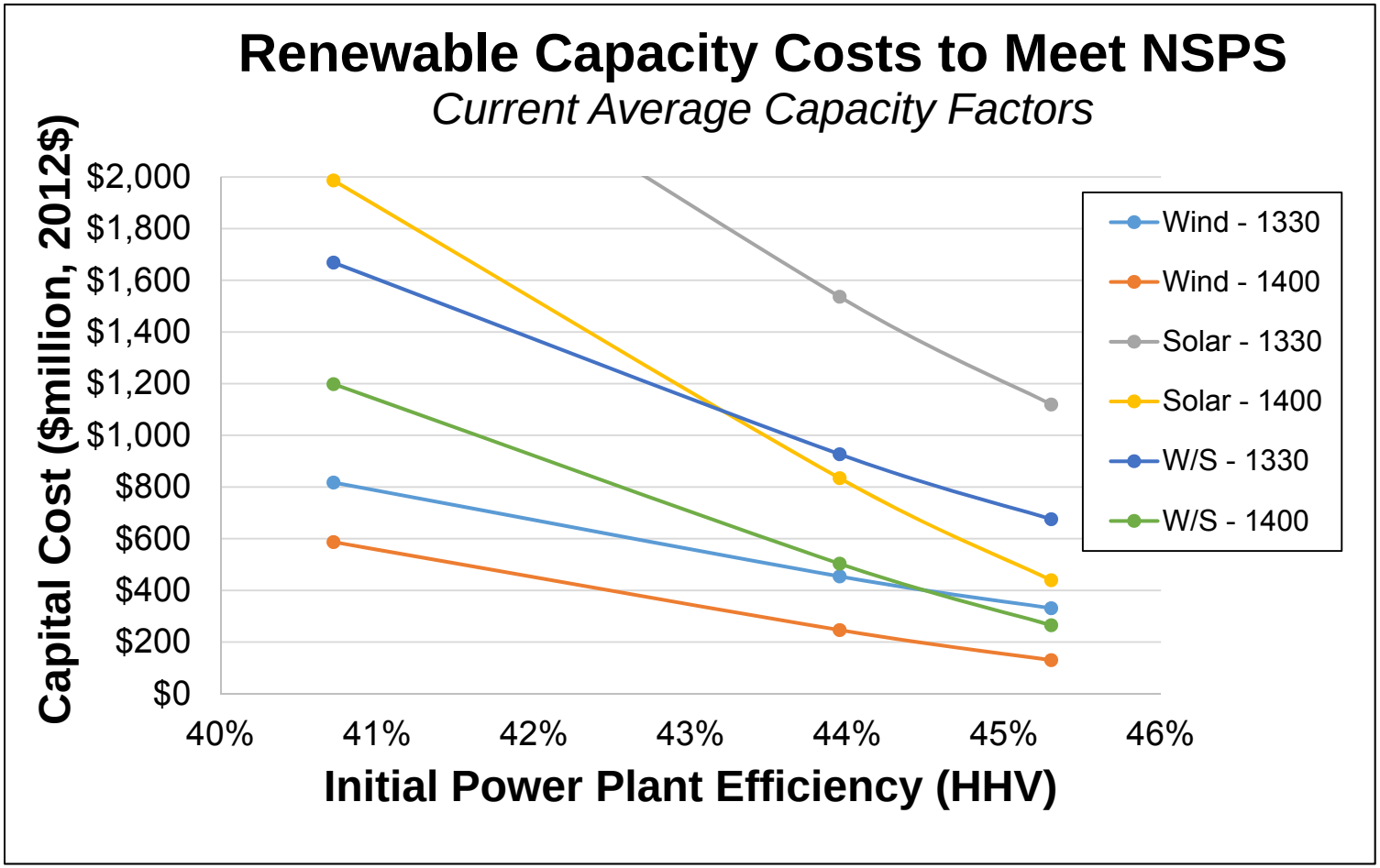
Direct Integration Results

Wind & Solar PV Capacity Requirements



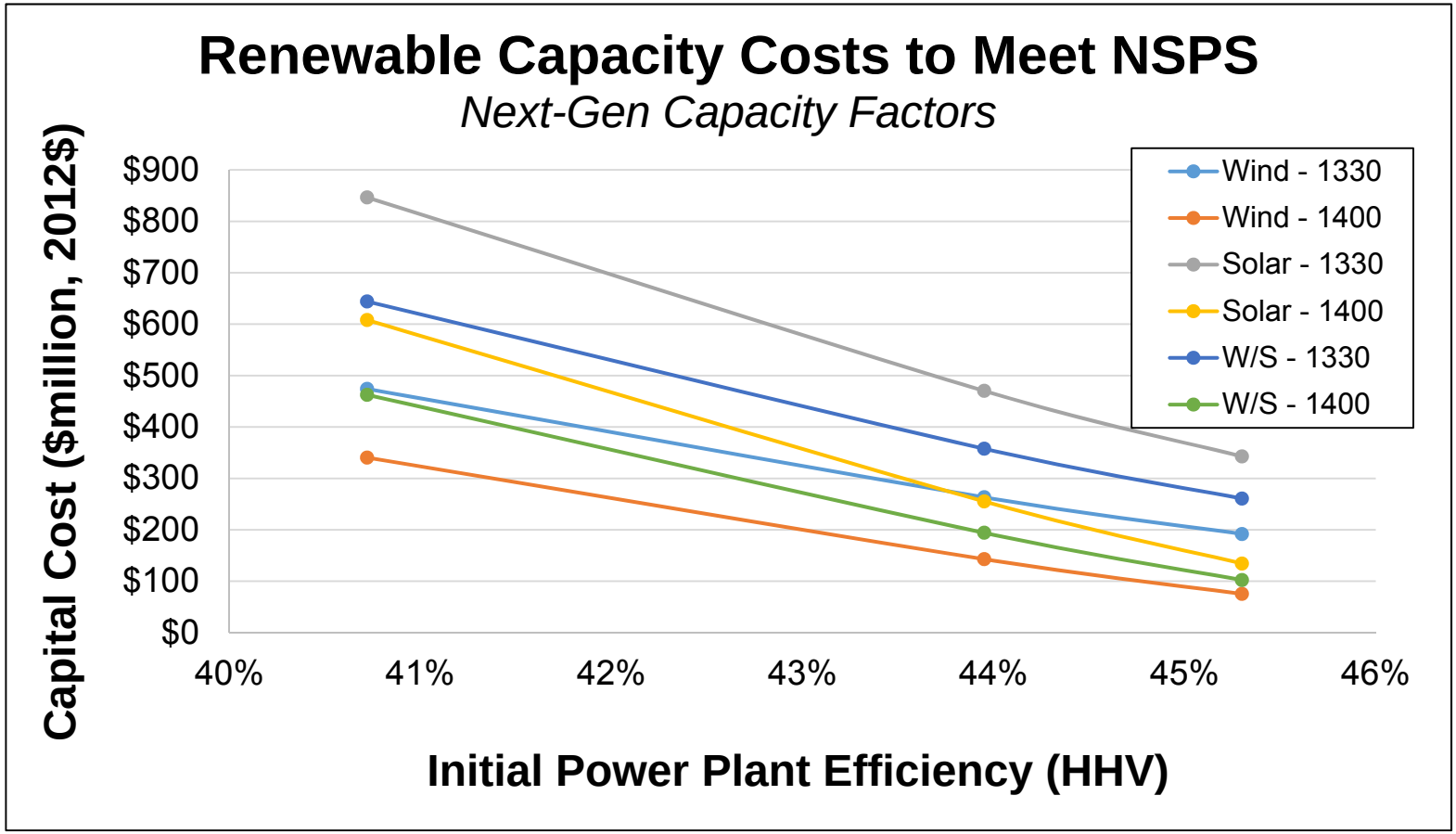
Direct Integration Results

Wind & Solar Total Overnight Capital Costs



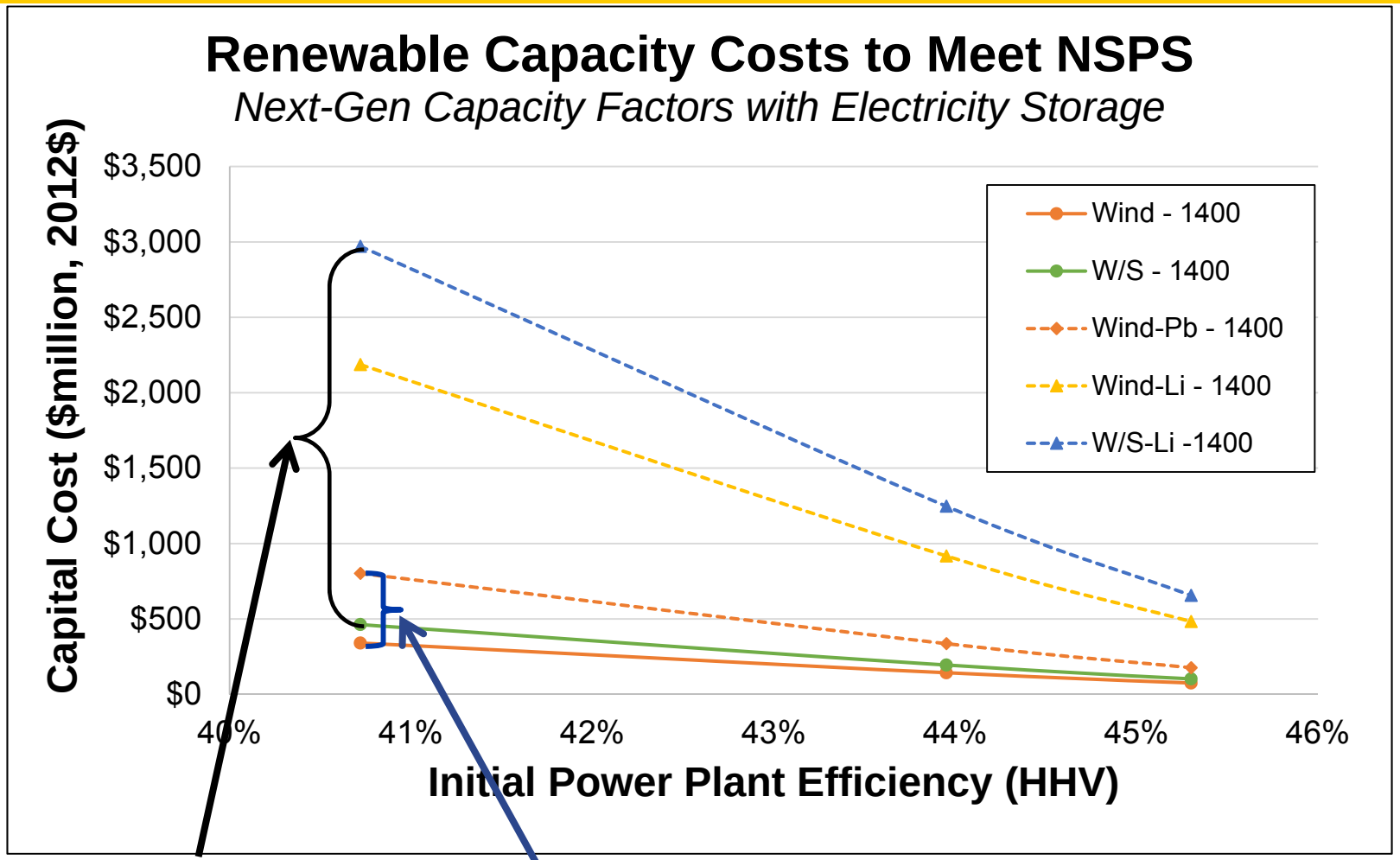
Direct Integration Results

Wind & Solar Total Overnight Capital Costs



Direct Integration Results

Total Overnight Capital Costs with Storage



Adding High Quality (Li-Ion) Storage not viable at "low" efficiencies

Cost Adder for Storage is High even for cases where Capacity Factors are Improved through R&D

Thermal Integration Results

Efficiency Improvement Targets to Meet NSPS

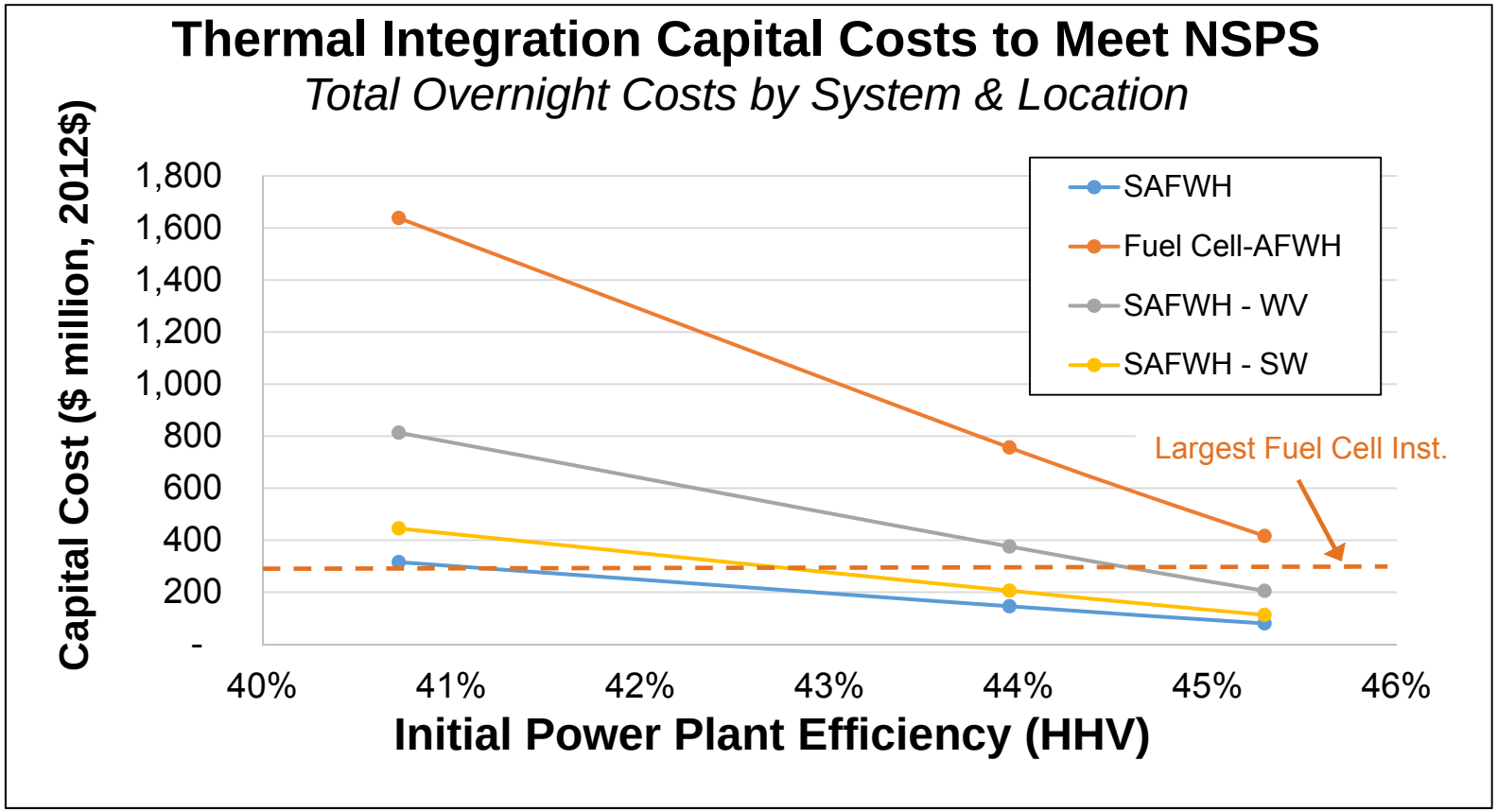
	Supercritical PC	High Efficiency USC	Next-Gen AUSC
Technology Readiness	State-of-the-Art	First-of-a-Kind*	TRL 5
Efficiency (HHV)	40.7%	44%	45.3%
Heat Rate (Btu/kWh)			
Net	8,373	7,764	7,531
Gross	7,950	7,456	7,270
Relative Heat Rate Improvement Required to Achieve 1,400 lb CO_2/MWh_g			
With Thermal Storage	13.5%	6.2%	3.4%
Without Thermal Storage	48%	22%	12%
Relative Heat Rate Improvement Required to Achieve 1,330 lb CO_2/MWh_g			
With Thermal Storage	18%	11%	8%
Without Thermal Storage	64%	39%	29%

** Efficiency matches that of the Trianel Lunen Power in Germany, one of the highest efficiency USC power plants in the world.*

Source: NREL Resource Assessment Program

Thermal Integration Results

Total Overnight Capital Costs with Storage



SAFWH Costs Evaluated for Three Different Scenarios

- Vendor Rated Output (SAFWH case, DNI: 12.5 7.5 kWh/m^2/day)
- Output at Generic Southwestern US Location (Annual Average DNI: 7.5 kWh/m^2/d)
- Output at Generic West Virginia Location (Annual Average DNI: 3.5 kWh/m^2/day)

Source: NREL Resource Assessment Program

Key Takeaways

- **Solar Feedwater Heating shows promise for near-term NSPS Compliance**
  - Technology is available at demonstration scale
  - Appears to be cost competitive in the near-term, even in areas with low levels of annual direct radiation
  - Requires thermal energy storage, but this is relatively low cost and demonstrated
  - Other considerations, such as geography and land availability could be constraints

- **Direct Integration of Wind Power may be near-term pathway to NSPS Compliance**
  - Could be competitive with Thermal Integration options at high efficiency USC facilities, assuming no storage
  - Requires replication of reported efficiencies at high efficiency USC plants like Lunen
  - Adding electricity storage may negate cost competitivenes at current SOA technology levels

- **Electricity Storage, particularly Li-Ion, not viable until higher efficiencies achieved**
  - Lithium Ion storage triples storage costs
  - Not viable at current SOA coal-fired power plant efficiencies (SCPC)

Key Takeaways (continued)

- **Solar Feedwater Heating better than Solar PV**
  - Solar PV isn't cost competitive with the efficiency improvements achievable through feedwater heating
  - Relative costs of thermal energy storage, which is somewhat inexpensive, versus electricity storage further drives this result

- **Fuel Cell Integration may not be a "now term" option**
  - System would be much larger than those commercially deployed
  - Next step is to contact a vendor to determine if other integration options exist

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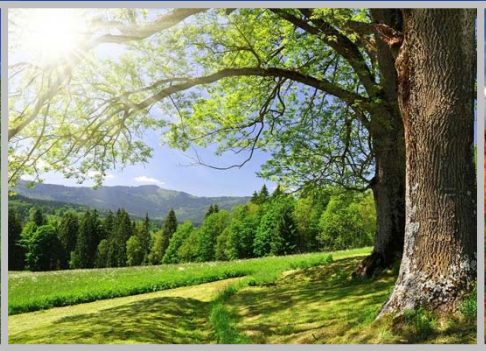


Backup slides

Additional Results

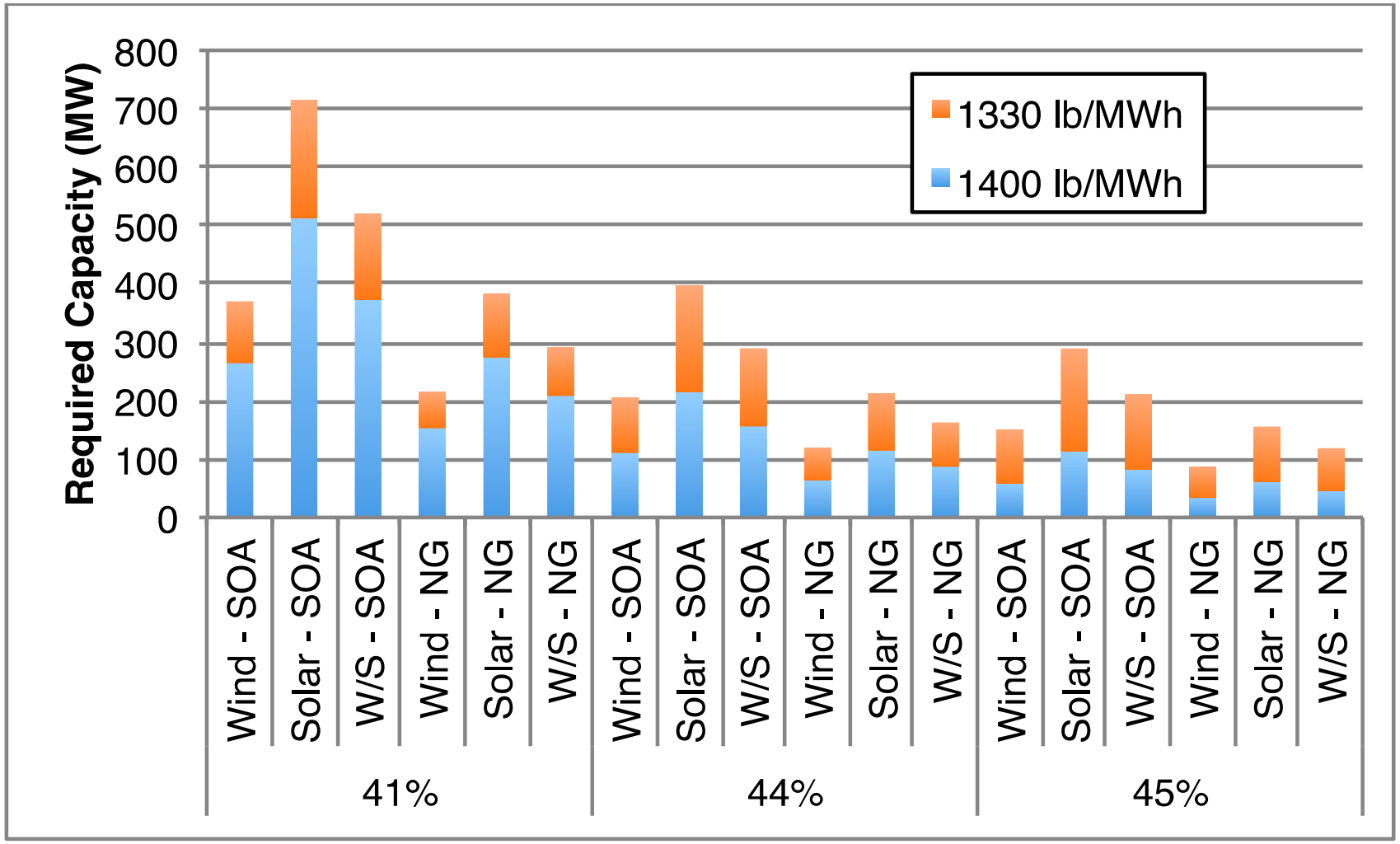
- **Boiler Feedwater Heating**
  - HPFWH Replacement can get all evaluated coal plants to 1,400 lb/MWh with thermal energy storage
  - All feedwater heaters may need to be replaced to get to 1,330 lb/MWh
  - LPFWH replacement may not be sufficient for any coal plant efficiency

- **Direct Integration of Renewables (Wind and Solar PV)**
  - Renewable capacities drop off with efficiency
    - » 126 MWe constant output required for SC PC
    - » 59 MW required for 44% high efficiency USC, 51 MW for 45.3% AUSC
    - » These capacity requirements are multiplied by the inverse of the annual capacity factor of the renewable resource being evaluated in order to determined required installed capacity
  - Storage requirements drop off commensurately with capacities
    - » Cost for SC PC and Lead Acid: $1.3 B; AUSC (44%): $524 MM
    - » Cost for SC PC and Lithium: $3.1 B; AUSC (44%): $1.4 B

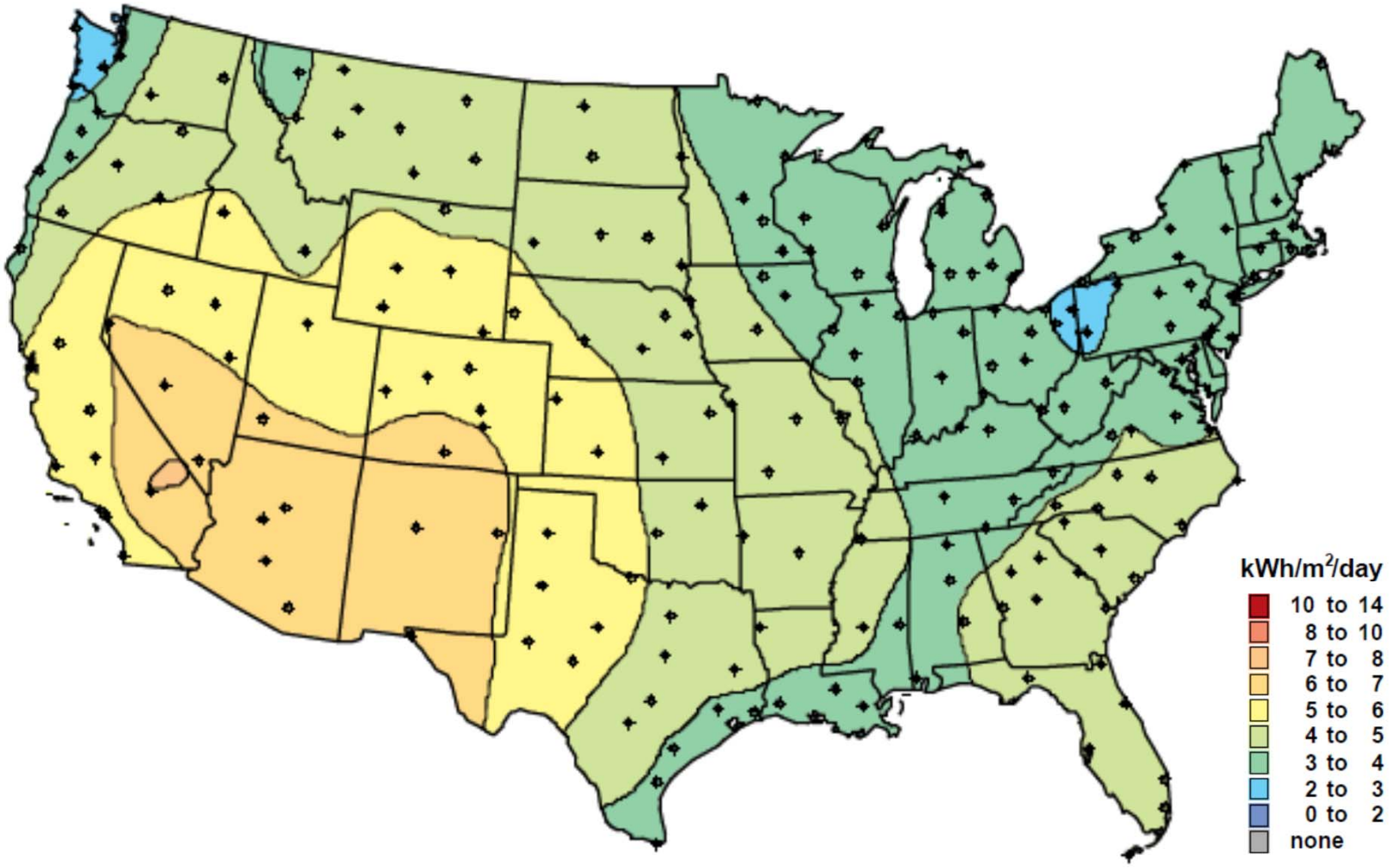
Additional Results

- **Integrating Fuel Cells**
  - 550 MW Supercritical PC would require:
    - » 363 MW of fuel cell generation
    - » $1.6 billion price tag
  - Higher Efficiency Coal Plants result in steep drop off in capacity & price
    - » Required capacity drops by 50% for High Efficiency USC, 45% more for Next Generation AUSC
    - » Price drops from $1,400/kW to $800/kW (kW of coal capacity)

Direct Integration Results



Average Daily Solar Radiation

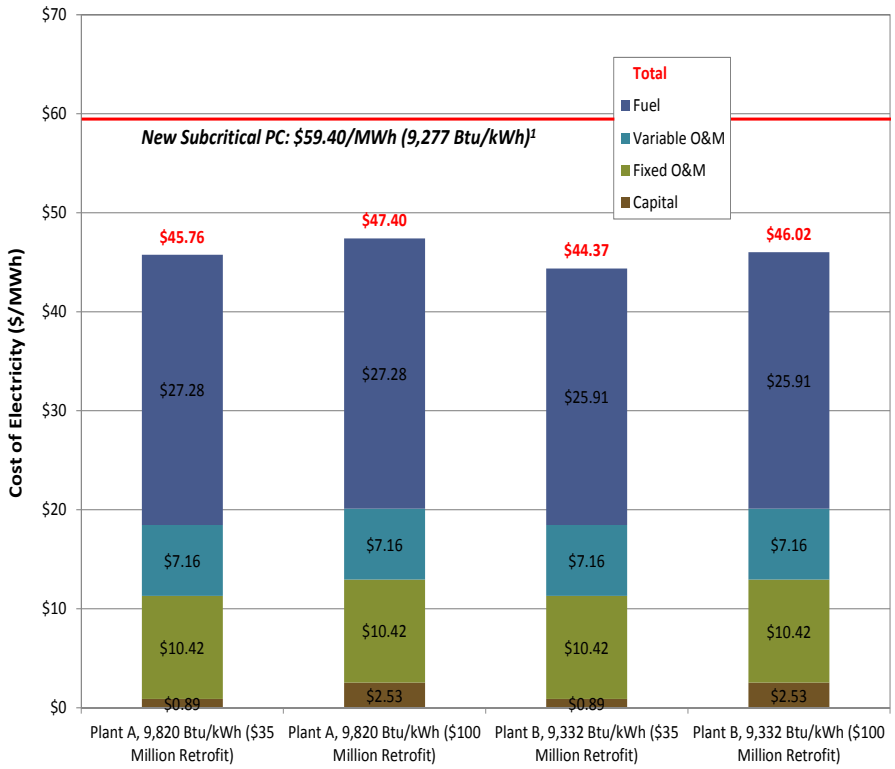


Source: NREL Resource Assessment Program

Economic Impacts

Retrofit costs

- Varied from $35-100M
- SA FWH system showed lower COE for both plant sites
- Tripling of retrofit costs did not overly affect COE
- The only results differences were for Capital and Fuel
  - Capital due to Solar Farm
  - Fuel due to transport distance



Performance & Emissions Impacts

- **Options for Improving the Efficiency of Existing Coal-Fired Power Plants**
  - 4/1/2014, DOE/NETL-2013/1611
  - Solar assisted (SA) feedwater heater (FWH) on sub-critical coal plant
  - Two plant locations:
    - Plant A - Phoenix, AZ
    - Plant B - Indianapolis, IN
  - Both locations:
    - 550 MW subcritical
    - 350,000 m^2 parabolic trough solar collection field
      - 710,000 m^2 for entire plant
    - 113,000 kg/hr extraction steam to last stage, high pressure FWH replaced by SA FWH
  - Performance
    - Plant A
      - 34.7% HHV (+2.4% points)
      - 7.1% emissions reduction
    - Plant B
      - 36.6% HHV (+1.4% points)
      - 3.6% emissions reduction

Cost & Performance Metrics

			Capacity Factors		Largest Existing Installation		Grid Mix -
	Costs ($/kW)		Next-Generation	Current (EIA)	Capacity (MW)	Acres	Multi Case
Solar PV	$3,873		28%	15%	290	3,200	60%
Onshore Wind	$2,213		50%	29%	1020	98,846	40%

Capacity Factor Sources:

- Current Capacity Factors, Upper Bound:
  - http://www.eia.gov/electricity/annual/html/epa_02_02.html
- "Next Generation" Capacity Factors:
  - http://www.nrel.gov/analysis/tech_cap_factor.html

Renewable Capital Cost Sources:

- Wind & Solar PV:
  - http://www.eia.gov/forecasts/capitalcost/pdf/updated_capcost.pdf
  - Derived from Andasol 2 Cost Data